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Nondestructive Assay for Nuclear Safeguards

LA-UR-21-

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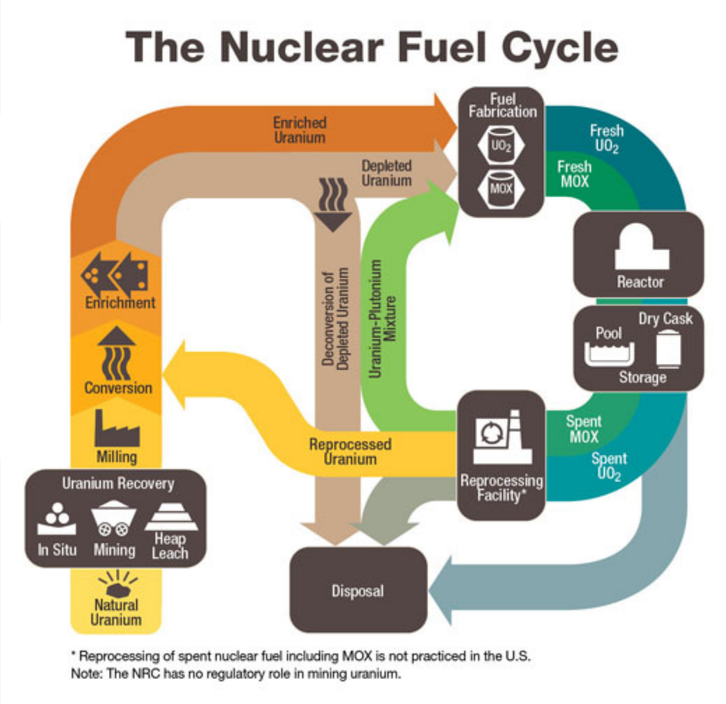
June 17, 2021

Safeguards and the
International Atomic Energy Agency

International Nuclear Safeguards

- Set of technical measures applied by the International Atomic Energy Agency (IAEA) to independently verify that nuclear materials are not being diverted to illicit purposes
- Safeguards play a central role in international nonproliferation efforts, i.e., in preventing the spread of nuclear weapons



- Tools and methods for implementing safeguards at nuclear facilities include:
  - Nuclear Material Accountancy
    - Nondestructive Assay (NDA)
    - Destructive Analysis (DA)
  - Containment & Surveillance
  - Environmental Sampling
  - Unattended and Remote Monitoring

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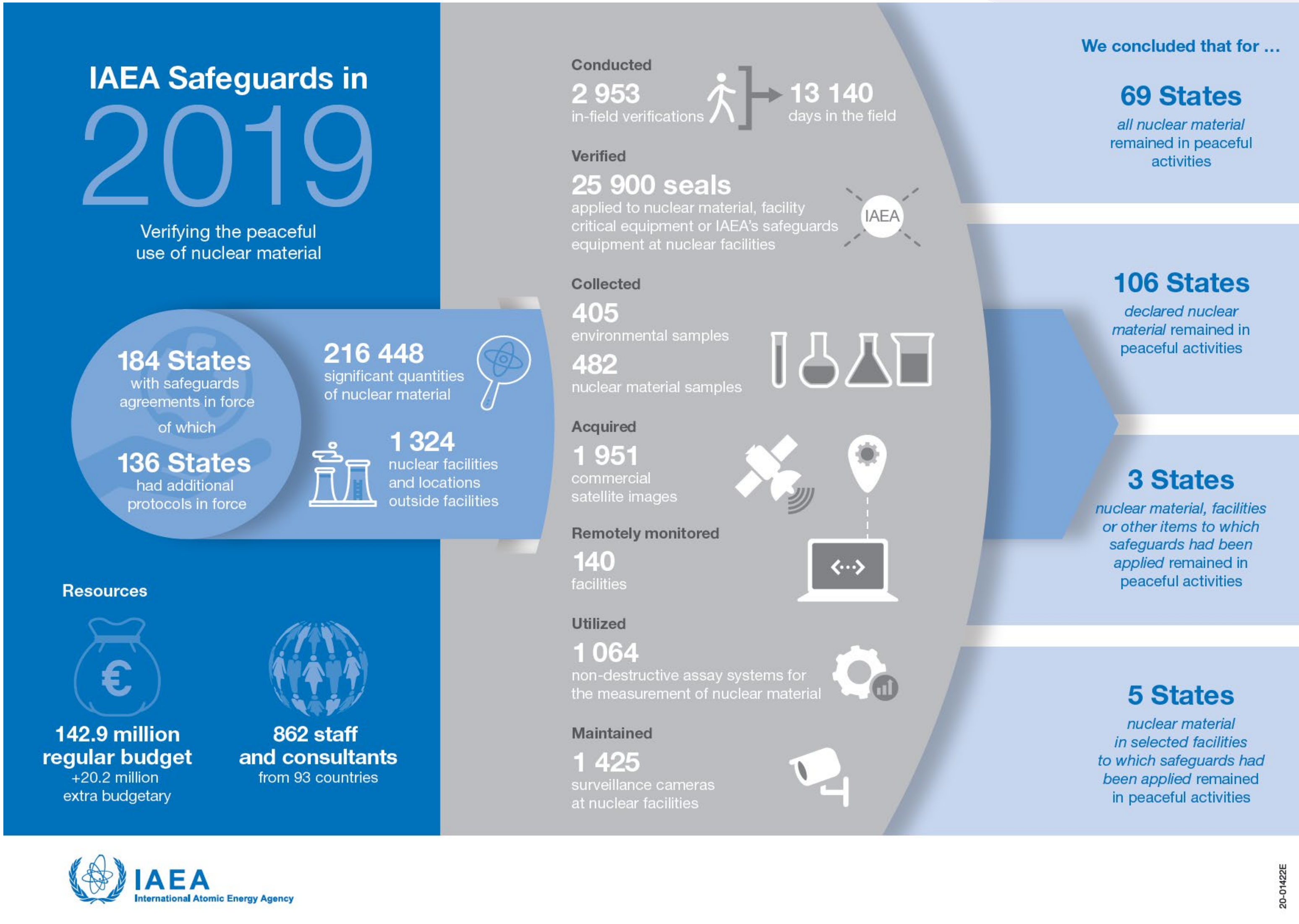
The International Atomic Energy Agency



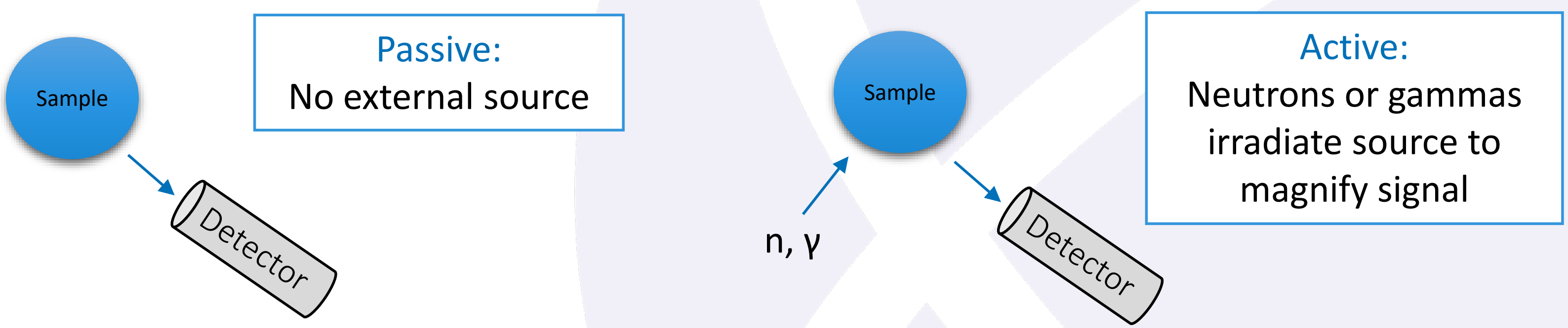
The International Atomic Energy Agency

- Currently, the IAEA is working to advance the following initiatives (among many others...)
  - Universal acceptance of the Additional Protocol
  - Safeguards-by-design
    - Integrated within a facility's design, covering safeguards and security
  - Unattended monitoring & data integration
    - Robust data management systems to reduce on-site inspector presence
  - State-level Concept
    - Assessing each State as a whole
    - Developing unified and consistent State-Level Approaches
    - Establishing safeguards measures based on path attractiveness rather than simply material attractiveness

Nondestructive Assay

Nondestructive Assay

- NDA is the most commonly employed technique for material accountancy
- A series of gamma or neutron detectors are typically used to measure radiation emitted from the sample of interest
- Energy, timing, and intensity of radiation may be correlated to isotope type and quantity in the sample



- Passive interrogation requires good signal intrinsic to sample (^{240}Pu, ^{252}Cf)
- Active interrogation requires fissile material or material prime for gamma interactions (^{235}U, ^{239}Pu)

Neutrons and Photons as NDA Signatures

Neutrons

Photons

Origins

- Spontaneous and induced fission
- (α,n)
- Cosmic rays
- (p,n)
- (n,2n)
- (γ,n)

Less common

- Nucleus (gamma-ray)
- Nuclear collision (gamma-ray)
- Electron cloud (x-ray)

Signal

Time and correlations

Energy

Shielding

Low Z material

High Z material

Detectors

^{3}He, Scintillators, fission chambers

HPGe, Scintillators, NaI, CZT, LaBr

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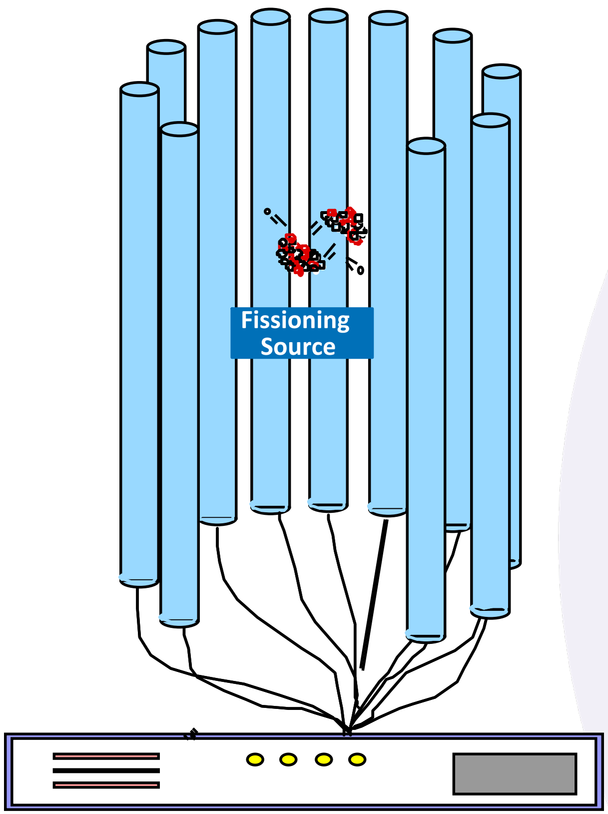
Neutrons

History of Neutron Counting for NDA

- TOTAL NEUTRON
  - Record the total number of neutrons detected in a certain amount of time
  - Accurate assays can be obtained only for very few types of SNM
- COINCIDENCE COUNTING
  - Record the number of times two neutrons arrive within a set time window (gate)
  - Wide application for international safeguards
    - focused on verifying declared materials
- NEUTRON MULTIPLICITY COUNTING
  - Extension of neutron coincidence counting
  - Record the number of times we detect 2, 3, 4, etc. neutrons within a gate
  - It improves neutron assay accuracy dramatically by adding more measured information

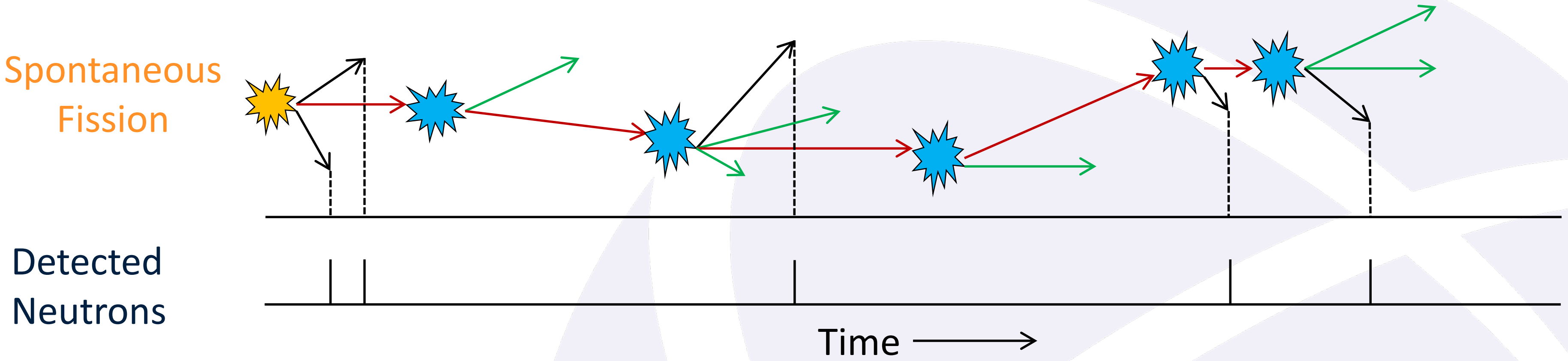
Neutron Coincidence Counter



Pulse-processing Electronics

- ^{3}He neutron detectors
- Fission source (Pu) surrounded by neutron detectors
- Emission of multiple **prompt** neutrons from fission detected as coincident neutron events
- Multiplicity information is used to calculate the mass of fissile isotopes

Neutron Coincidence Counting



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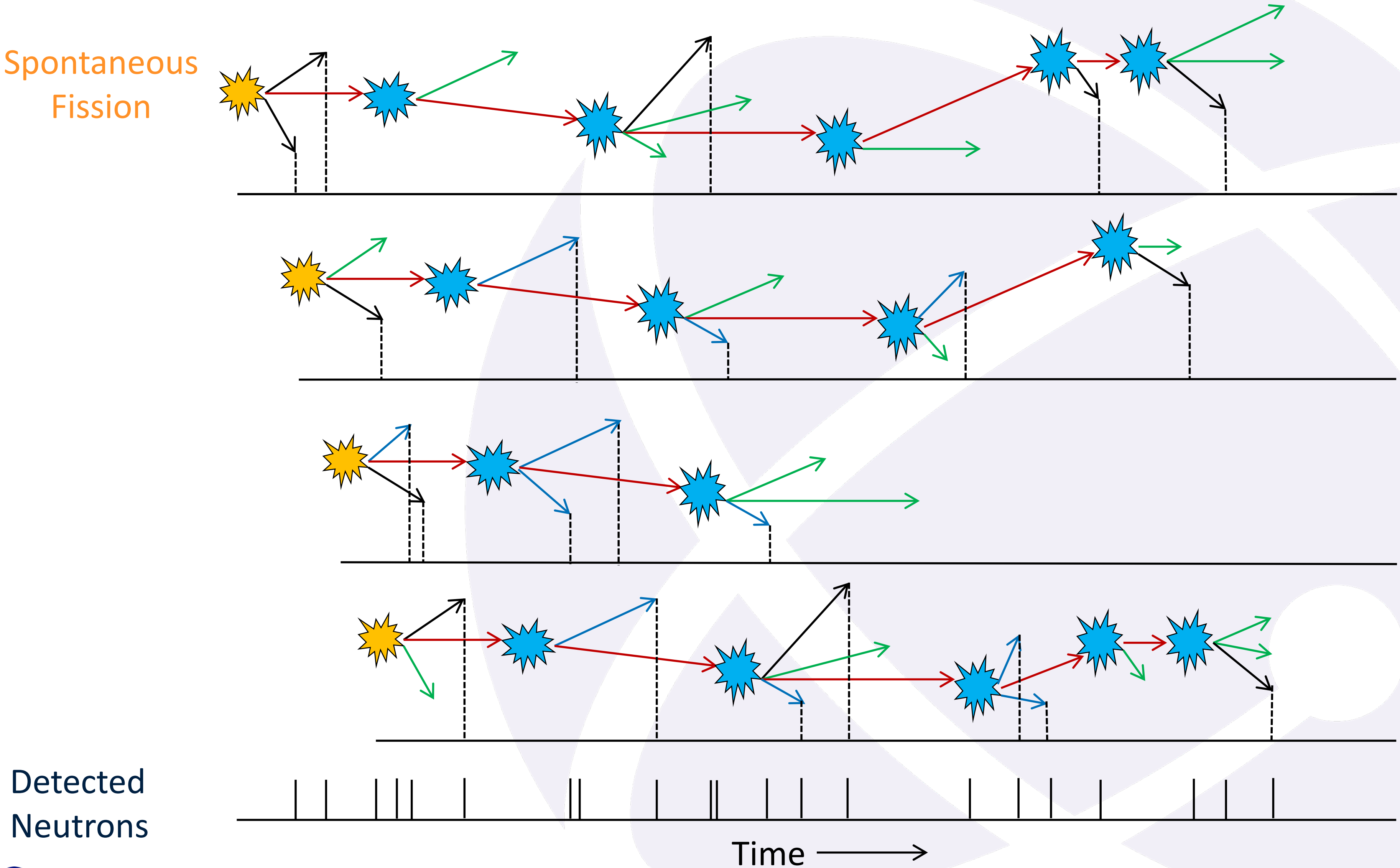
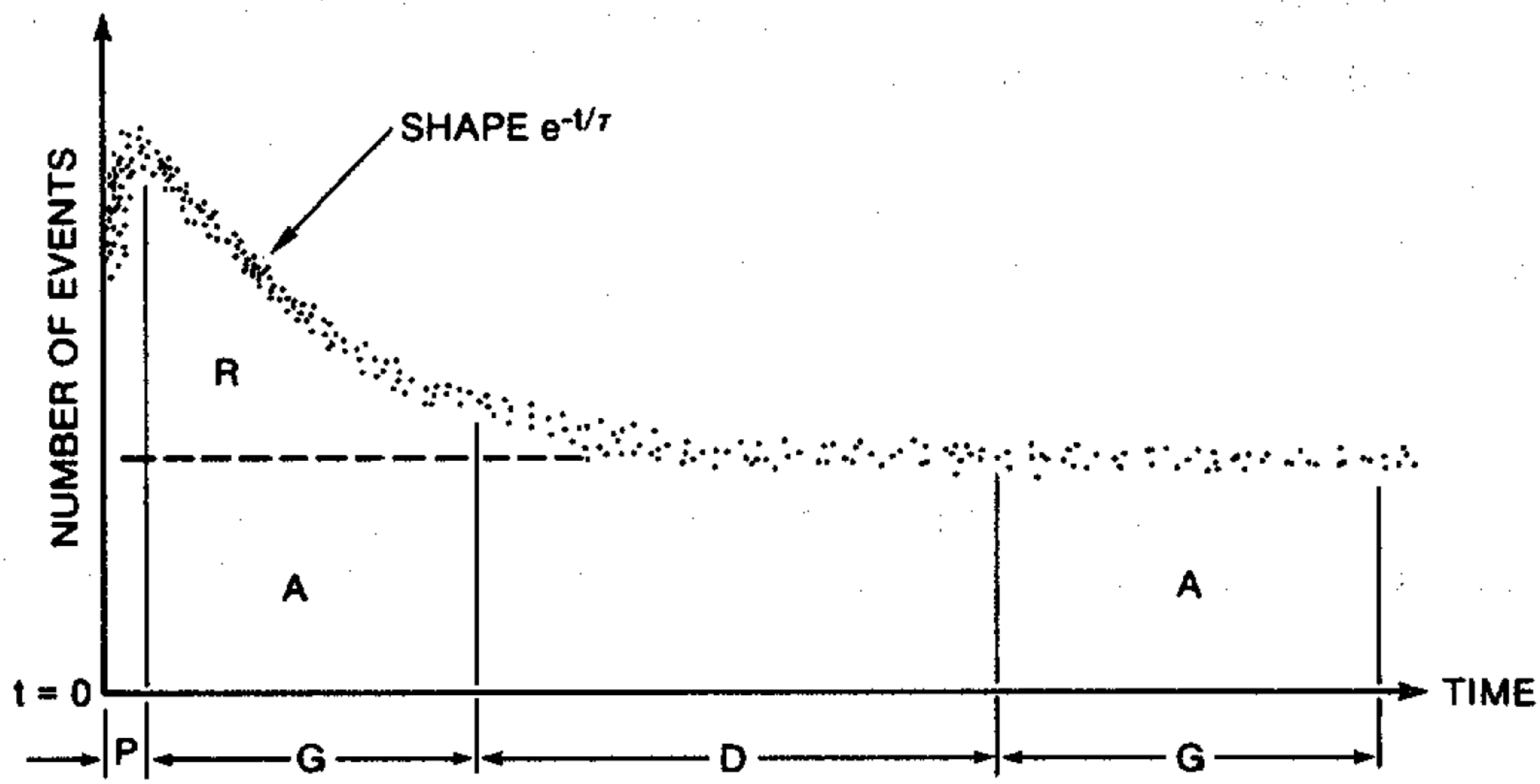
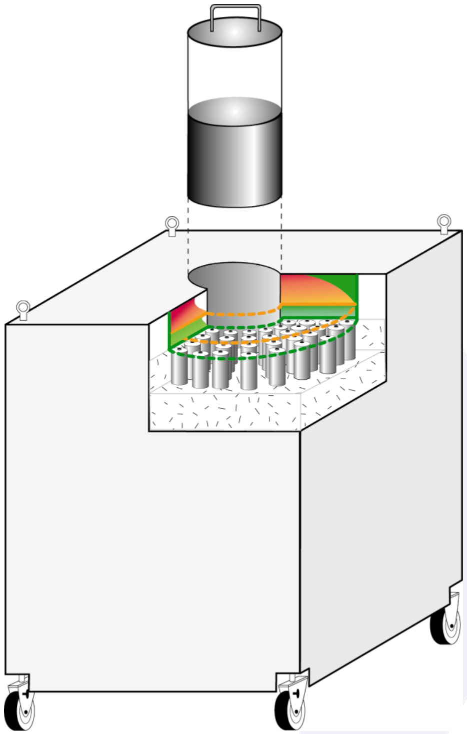
Neutron Coincidence Counting



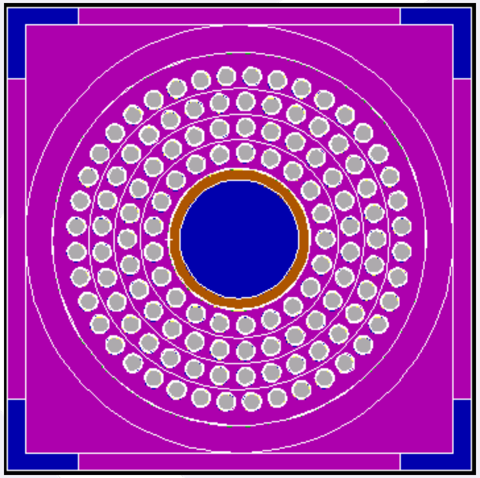
Rossi-Alpha Distribution



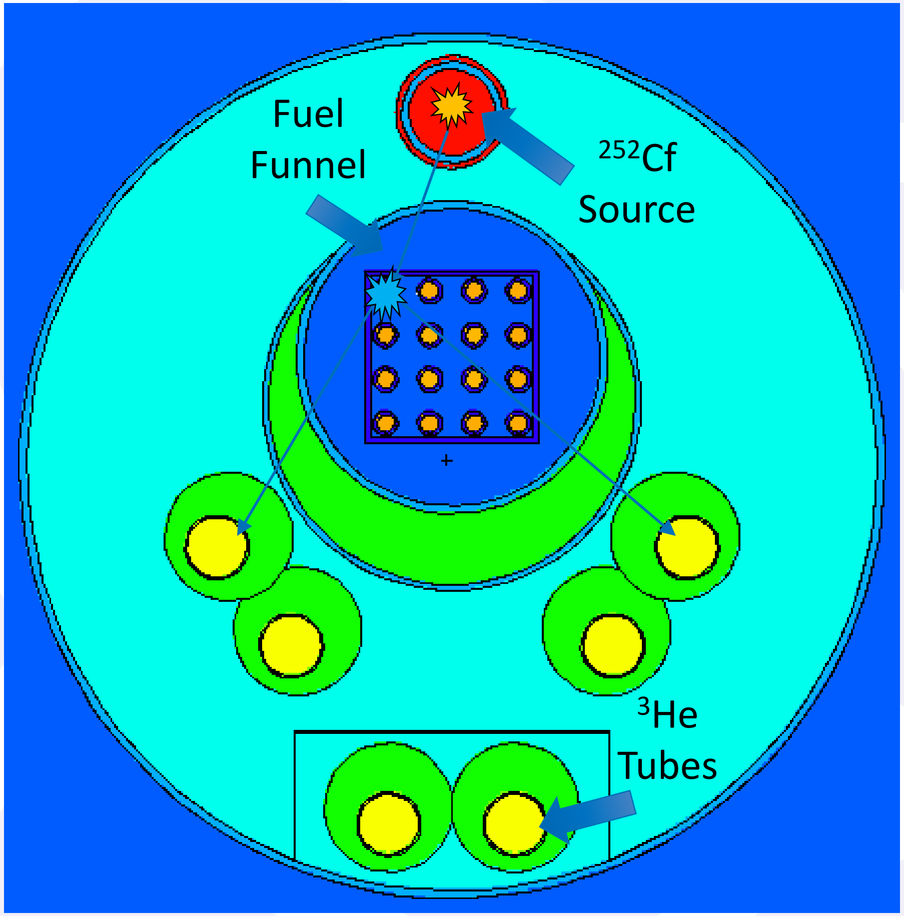
Epithermal Neutron Multiplicity Counter (ENMC)



- ε = 65.0%
- τ = 22.0 μsec
- 121 tubes
- 27 preamplifier channels

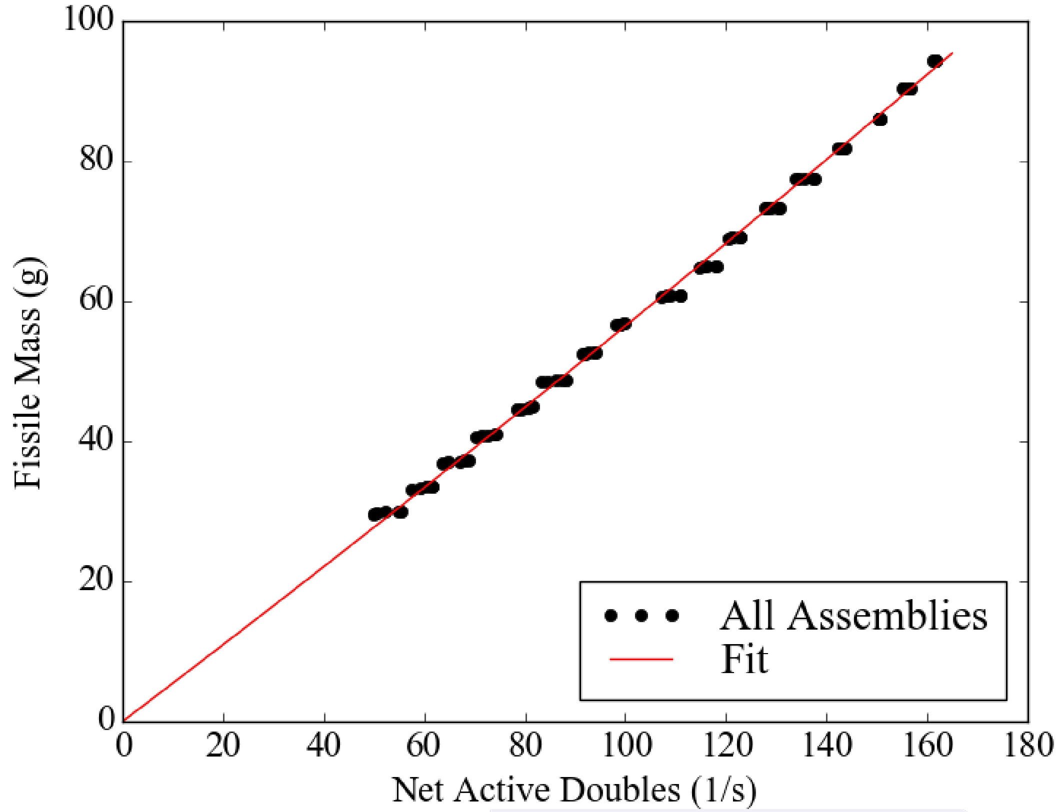


Advanced Experimental Fuel Counter



Advanced Experimental Fuel Counter

Active Doubles – Passive Doubles – Cf Doubles = Net Active Doubles



Gamma Rays

Photons

Generic Assay Equation

$$M_{SNM} = \frac{R_{Rad} \times CF}{Cal}$$

M_{SNM} = Mass of special nuclear material

R_{Rad} = Measured radiation rate (counts per unit time) from SNM item

CF = Correction for losses due to:

- item self absorption
- container absorption
- measurement system electronics

Cal = Calibration constant

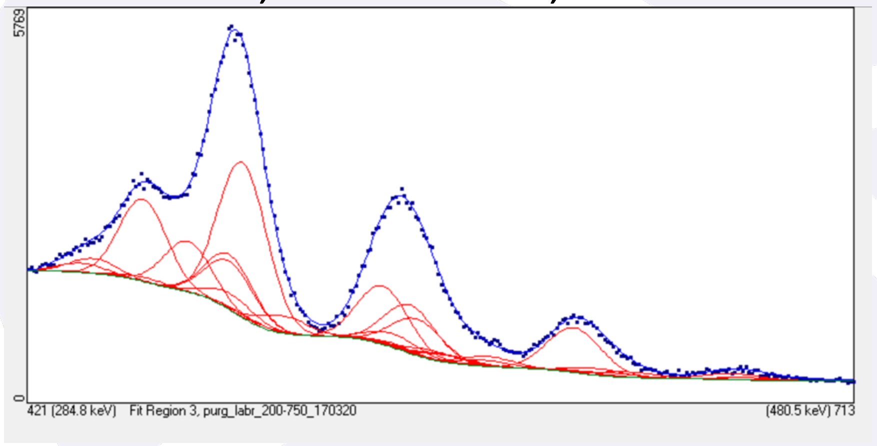
FRAM

- FRAM is an isotopic analysis code nominally designed for plutonium and uranium.
- Fixed-energy Response-function Analysis with Multiple efficiencies.
- Self-calibration using several gamma-ray peaks.
- User-editable analysis parameters.
- Analyze gamma ray data from 30keV to >1MeV of HPGe, CdTe, CZT, and LaBr3 detector.

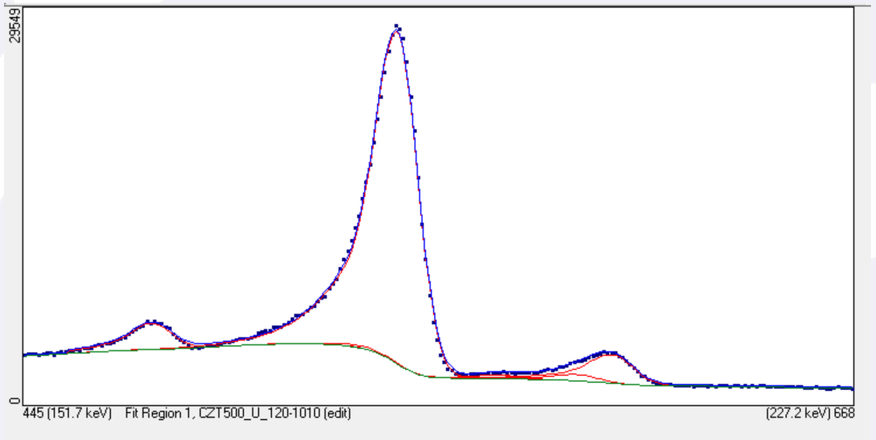
Peak Fitting

- FRAM uses linear least squares to fit the peaks of the HPGe spectra.
- FRAM uses a nonlinear least squares fit technique, combining the Powell's minimization method with the linear least squares fit to fit the peaks of the LaBr3 and CZT spectra.

Pu, 285-481 keV, LaBr3

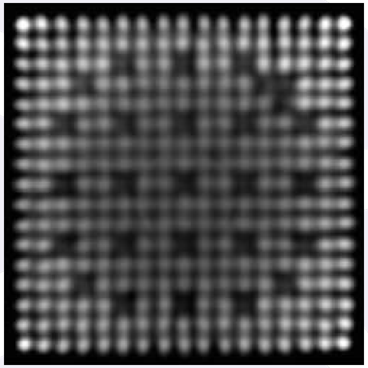


U, 152-226 keV, CZT

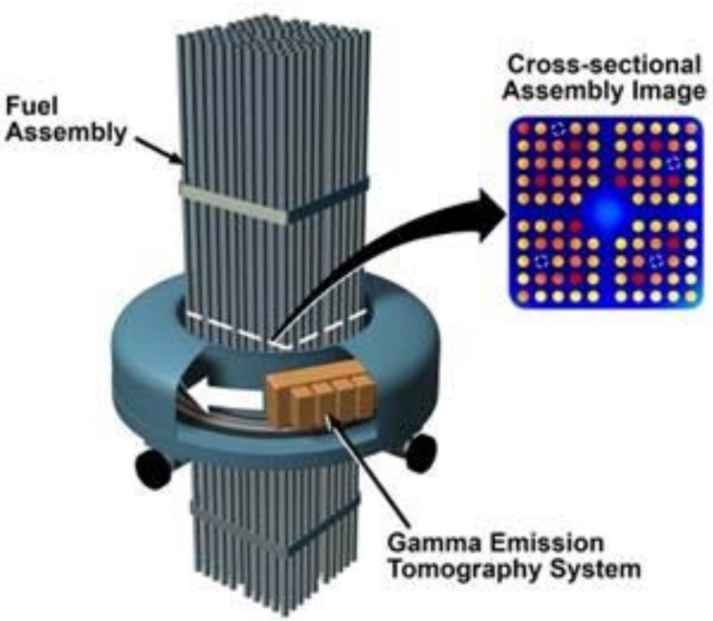


Passive Gamma Emission Tomography (PGET)

- Three simultaneous measurements: gross neutron, gamma spectroscopy, and 2D emission tomography
- Create an axial image of emission locations to detect pin-level diversions
- Measurements take 3-5 minutes



Mayorov et al., IEEE, 2017



Miller et al., PNNL, 2017

- Neutron data are used for BU, spectroscopy data for CT or to verify non-fuel items
- Has been tested for burnups from 5.7-58 GWd/tU and cooling times from 1.9-27 years

Heat

Calorimetry

- Well-established, precise method of NDA
- Uses thermal power generated by radioactive decay in the sample to determine the mass of special nuclear material
- Heat flow calorimetry is most commonly used for materials control and accounting
- 60 Wheatstone bridge calorimeters currently being used for Pu and tritium measurements at LANL
- Bulk measurements can be taken without issues from absorption or self-shielding
- Takes much longer than other NDA techniques

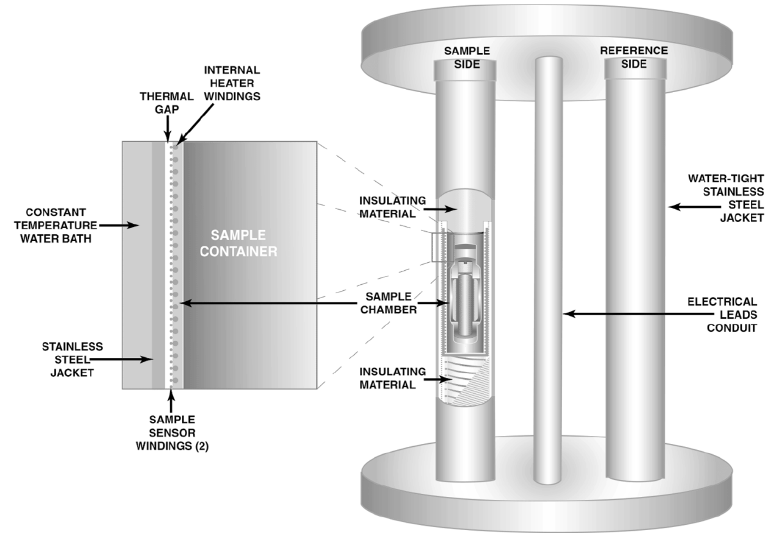
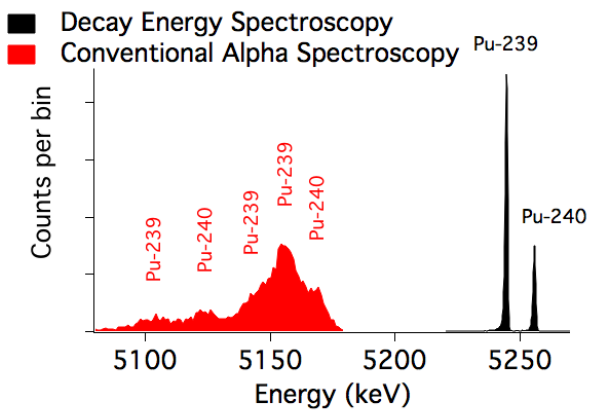


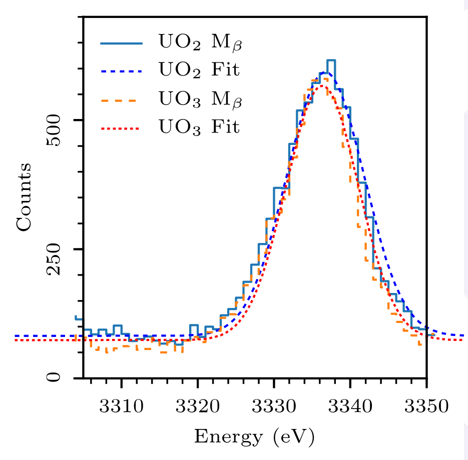
Figure 3. Schematic of a twin-bridge heat-flow calorimeter with basic components labeled.

Microcalorimetry

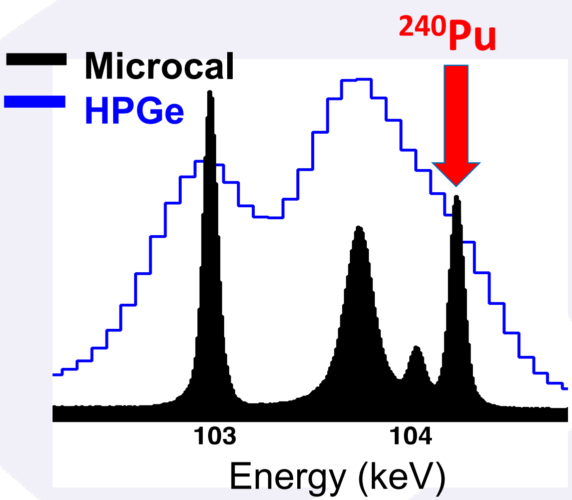
- Ultra-high energy resolution microcalorimeter technology offers a path to overcome NDA performance limits
  - *10-50x better energy resolution than semiconductor detectors*
- Improve economics and performance of safeguards and material accounting approaches



Decay energy spectroscopy



X-ray spectroscopy



Gamma-ray spectroscopy

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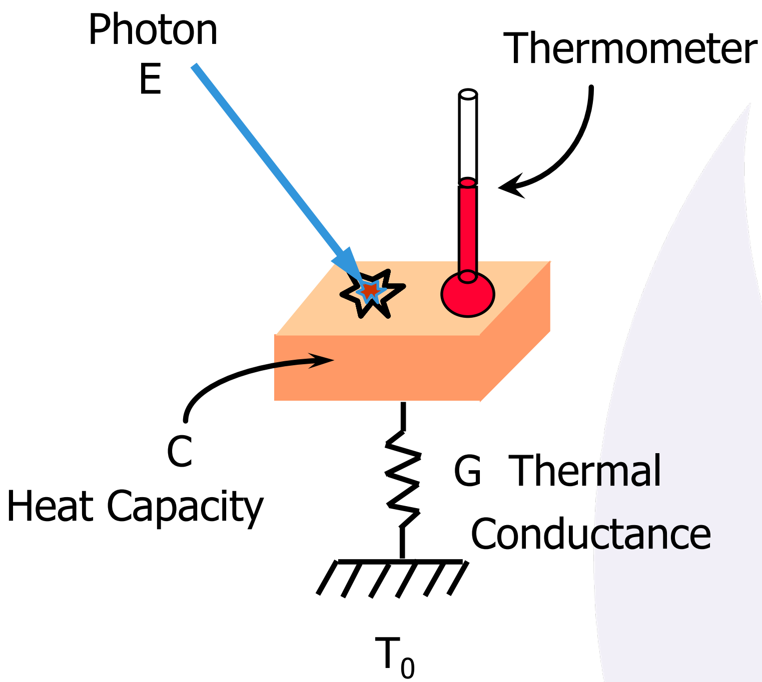
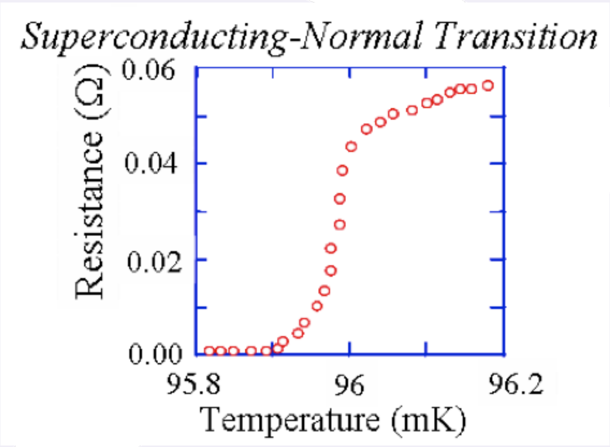
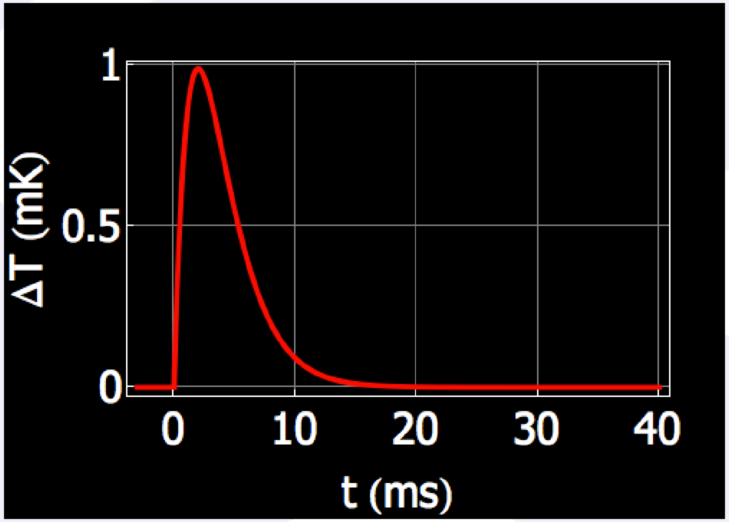
Microcalorimeters measure the heat energy of individual photons or nuclear decays



$$E = C \times \Delta T$$

$$\Delta E \approx \sqrt{4kT^2C}$$





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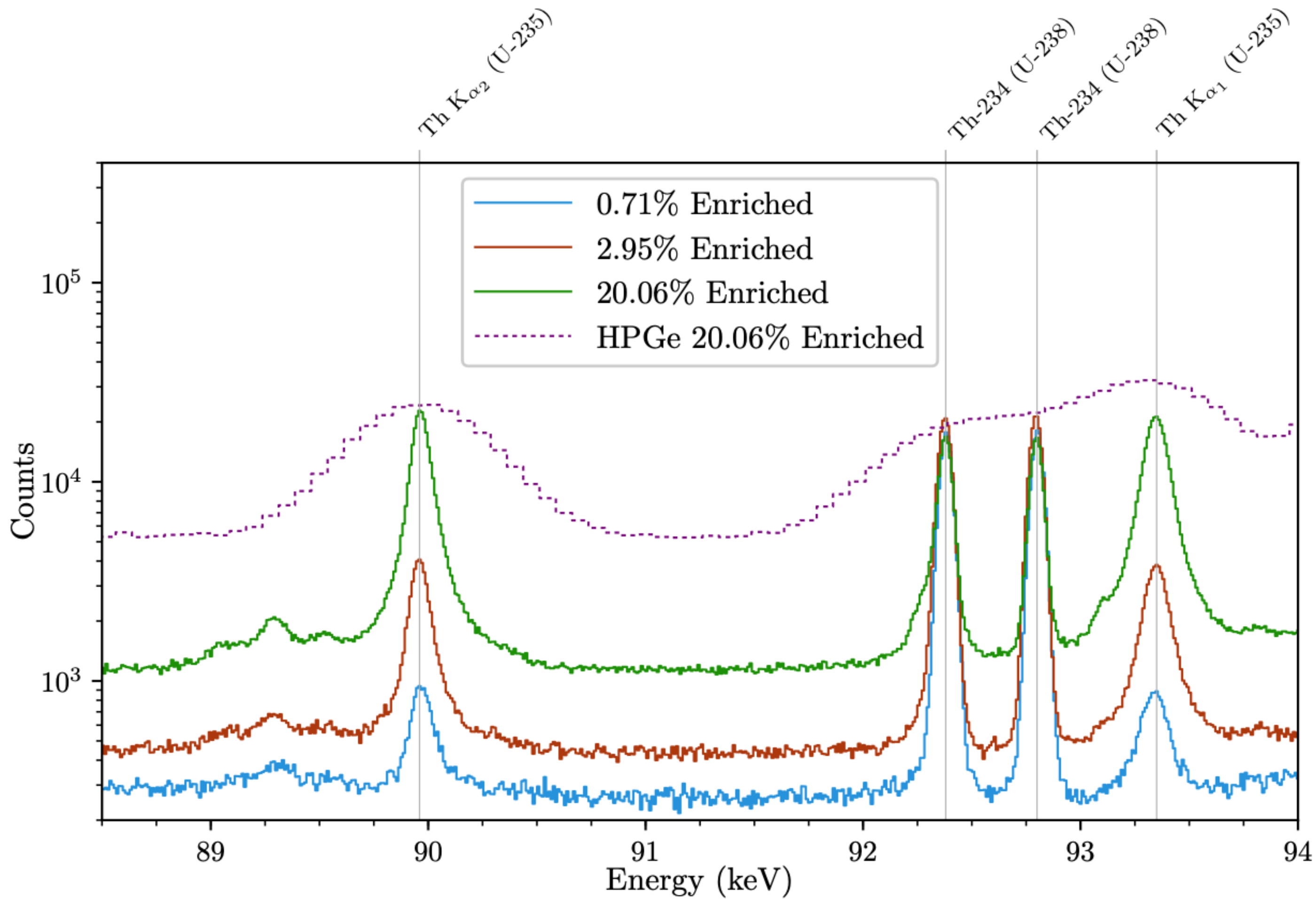
Potential to improve nondestructive measurements of ^{235}U enrichment



Safeguards Research at LANL

LANL Support

Over 50 years of support for the IAEA through…

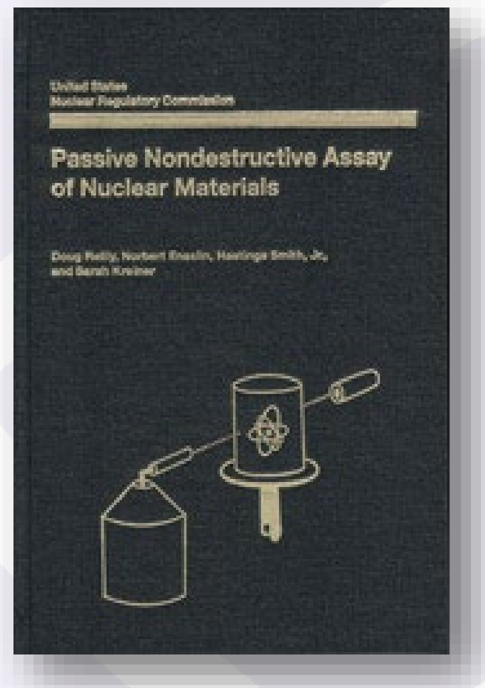
Technology development

Training

Expertise

Updated PANDA Manual

- An updated version of the PANDA manual (published in 1990) will be released soon
- New addenda
- New technologies
- New characterization methods
- New electronics
- …much more!



Thank you!

Questions?